frontiers in Nutrition

REVIEW
published: 20 August 2019
doi: 10.3389/fnut.2019.00131

Is an Energy Surplus Required to Maximize Skeletal Muscle Hypertrophy Associated With Resistance Training

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Specialty section:
This article was submitted to Sport and Exercise Nutrition, a section of the journal Frontiers in Nutrition

Received: 08 April 2019
Accepted: 02 August 2019
Published: 20 August 2019

Citation:
Slater GJ, Dieter BP, Marsh DJ, Helms ER, Shaw G and Iraki J (2019) Is an Energy Surplus Required to Maximize Skeletal Muscle Hypertrophy Associated With Resistance Training. Front. Nutr. 6:131. doi: 10.3389/fnut.2019.00131

Resistance training is commonly prescribed to enhance strength/power qualities and is achieved via improved neuromuscular recruitment, fiber type transition, and/ or skeletal muscle hypertrophy. The rate and amount of muscle hypertrophy associated with resistance training is influenced by a wide array of variables including the training program, plus training experience, gender, genetic predisposition, and nutritional status of the individual. Various dietary interventions have been proposed to influence muscle hypertrophy, including manipulation of protein intake, specific supplement prescription, and creation of an energy surplus. While recent research has provided significant insight into optimization of dietary protein intake and application of evidence based supplements, the specific energy surplus required to facilitate muscle hypertrophy is unknown. However, there is clear evidence of an anabolic stimulus possible from an energy surplus, even independent of resistance training. Common textbook recommendations are often based solely on the assumed energy stored within the tissue being assimilated. Unfortunately, such guidance likely fails to account for other energetically expensive processes associated with muscle hypertrophy, the acute metabolic adjustments that occur in response to an energy surplus, or individual nuances like training experience and energy status of the individual. Given the ambiguous nature of these calculations, it is not surprising to see broad ranging guidance on energy needs. These estimates have never been validated in a resistance training population to confirm the "sweet spot" for an energy surplus that facilitates optimal rates of muscle gain relative to fat mass. This review not only addresses the influence of an energy surplus on resistance training outcomes, but also explores other pertinent issues, including "how much should energy intake be increased," "where should this extra energy come from," and "when should this extra energy be consumed." Several gaps in the literature are identified, with the hope this will stimulate further research interest in this area. Having a broader appreciation of these issues will assist practitioners in the establishment of dietary strategies that facilitate resistance training adaptations while also addressing other important nutrition related issues such as optimization of fuelling and recovery goals. Practical issues like the management of satiety when attempting to increase energy intake are also addressed.

Keywords: muscle hypertrophy, sports nutrition, resistance exercise, diet, nutrient timing

INTRODUCTION

Resistance training is commonly prescribed to increase underlying strength and power qualities in an attempt to improve athletic performance. The enhancement of these qualities may be derived from a range of potential adaptations including improved neuromuscular recruitment, fiber type transition, and/ or skeletal muscle hypertrophy. Promoting hypertrophy is especially important in strength sports, given the strong relationship between fat free mass (FFM) and competitive lifting performance (1, 2). Furthermore, in contact sports such as rugby union, larger players have a clear advantage (3) which is highlighted in World Cup data where total mass of forwards is correlated with success (4, 5). Amongst elite youth rugby league players, quadriceps muscle hypertrophy is related to enhancement of running speed (6). However, this may not be appropriate for all athletes with skeletal muscle hypertrophy possibly resulting in adverse adaptations, including a transition away from fast twitch glycolytic fibers and slower contraction velocity characteristics (7) if inappropriately prescribed. Thus, unless the increase in power proportionally exceeds any associated weight gain, performance is unlikely to be enhanced by skeletal muscle hypertrophy. Collectively there is support for the potential of skeletal muscle hypertrophy enhancing athletic performance, but individual athlete nuances must be considered by coaching personnel and training prescribed so as to facilitate adaptations in both muscle hypertrophy and power so that any associated increase in body mass does not negatively affect variables like speed (8).

The manipulation of dietary intake is common among individuals attempting to facilitate resistance training gains in strength and skeletal muscle hypertrophy. Aside from water (75%), skeletal muscle is made up of protein (20%), with the remainder from other materials including fat, glycogen, inorganic salts, and minerals (9). Given the protein content of skeletal muscle, it is perhaps not surprising resistance trained athletes emphasize the importance of dietary protein in their meal plans (10). This is also reflected in the scientific literature with significant attention given to protein focused nutritional interventions to facilitate resistance training induced adaptations (11), including manipulation of total daily dietary protein intake (12), protein dosage per meal (13–15), protein quality (16), and protein distribution (17). While a recent meta-analysis suggested dietary protein supplementation enhances resistance training induced gains in muscle mass and strength, at least when dietary protein intake is suboptimal (<1.6 g·kg^{-1} daily) (18), resistance training alone provides a far greater stimulus than protein supplementation (14). Given this, a number of other dietary strategies have previously been proposed to augment the resistance training response, including the creation of a positive energy balance (19, 20). While facilitating a positive energy balance is not supported by others because of the potential for increments in fat mass (FM) (21), there is clear evidence of a whole body anabolic response to overfeeding, even in the absence of a resistance training stimulus in sedentary populations (22, 23). This raises a question about composition of the lean mass accretion in this scenario i.e., skeletal muscle vs. splanchnic protein (24), especially given the lack of change in mammalian target of rapamycin (mTOR) (25). Furthermore, additional energy does not appear to further modulate the acute muscle protein synthesis (MPS) response to dietary protein ingestion at rest (26), or following resistance exercise (27, 28). Despite this, numerous textbooks used in the training of nutrition professionals advocate the creation of an energy surplus when attempting to facilitate skeletal muscle hypertrophy (29–32).

The exact energy cost of skeletal muscle hypertrophy is not known. Likewise, it is not clear if this energy cost can be met purely from endogenous (i.e., internal fat stores) and/or exogenous sources (i.e., diet). Indeed, there is clear evidence of marked skeletal muscle hypertrophy in response to a novel resistance training stimulus in otherwise healthy, overweight individuals in conjunction with a hypoenergetic, higher protein meal plan (33, 34). While similar concurrent reductions in FM and gains in FFM have been observed in elite and professional athletes following return to sport after an off-season break (35) or injury (36, 37), this response is less evident in highly trained individuals exposed regularly to a resistance training stimulus (38). This raises the possibility that individual nuances may need to be considered, including energy status and training history. Indeed, there is research confirming initial body fat stores influence metabolic response to starvation (39), while individuals with higher FFM and cardiorespiratory fitness gain less FM relative to FFM during isoenergetic, isonitrogenous overfeeding in a sedentary state (40). Preliminary research indicates younger athletes experience more pronounced physique and physical characteristic training adaptations compared to their older peers (41), a trend also even amongst mature professional athletes (38). A better appreciation of these individual nuances may assist with establishing realistic training adaptation aspirations, plus prescription of training and diet interventions to facilitate skeletal muscle hypertrophy.

It is not known if any adjustment in dietary intake to support muscle hypertrophy is required to merely contribute the building blocks of skeletal muscle while also accounting for the metabolic cost of generating new skeletal muscle mass (SMM), or if the physiological response to an energy surplus amplifies the anabolic signal created by resistance training. Addressing these fundamental questions is paramount to future prescription of energy intake guidance associated with dietary strategies to optimize skeletal muscle hypertrophy. Given the dearth of research specifically examining the influence of an energy surplus on resistance training outcomes, an exploration of overfeeding studies independent of resistance exercise has also been included in this review. This needs to be considered, given the impact of resistance training on sensitivity to nutrition support. Indeed, a single resistance training session can serve to potentiate MPS in response to protein feeding (42), an effect which may persist for upwards of 24–48 h after resistance exercise (43, 44).

Overfeeding alone is not sufficient to produce favorable body composition changes such that proportionally more FFM is gained than FM. Indeed, while 100 days of energy surplus (totaling 353 MJ) among young lean males resulted in significant individual variation in body composition change, ∼2 kg of FM were accrued for each 1 kg of lean mass (45). In Leaf and Antonio's summary of overfeeding studies, they also note that predominantly more FM is gained with overfeeding in the absence of resistance training (46). However, it seems unlikely that overfeeding alone would produce meaningful increases in contractile tissue as the initiating event which induces skeletal muscle hypertrophy after maturation is the production of sufficient tension (47) and subsequent mechanotransduction at the muscle fiber level (48). In an exercise or strength and conditioning setting, this stimulus is supplied via progressive resistance training. Other related factors such as the resultant muscle damage, metabolic fatigue, and hormonal response to resistance training are speculated to either correlate with, be additive to, or play a permissive role in training-induced hypertrophy, but are not yet fully understood (49). It is plausible that nutrition could influence some of these factors.

This review not only addresses the impact of energy balance on resistance training outcomes, with an emphasis on skeletal muscle hypertrophy, but also explores other important issues, including "how big should the energy surplus be," "where should the extra energy come from," and "when should this extra energy be consumed." Having a broader understanding of these issues will help establish nutrition strategies to optimize resistance training adaptations and at the same time address nutritional issues such as optimizing recovery and fuelling goals. A broader understanding of the physiological implications of an energy surplus not only has clear application to the resistance trained athlete but may also be applicable to clinical populations where retention or promotion of SMM may be advantageous. While it is recognized supplement use is common amongst resistance trained athletes (50), and there is empirical evidence to support the use of supplements like creatine monohydrate in facilitating resistance training adaptations (51), the focus of this review remains with exploring the impact of energy balance on resistance training outcomes.

ENERGY BALANCE

The daily energy cost of protein turnover accounts for ∼20% of resting energy needs or 18 $kJ \cdot kg^{-1}$ body mass (52). Skeletal muscle hypertrophy requires the further remodeling of muscle, ensuring it is an energy intensive process. As such, there has been much discussion around the role of energy balance (i.e., energy surpluses, energy deficits, and isocaloric states) in modulating hypertrophy. Currently, there is a paucity of literature that directly addresses the precise role energy deficits, surpluses, and net balance states play in muscle hypertrophy.

Only a few studies have directly assessed the role of energy balance on skeletal muscle hypertrophy in response to resistance training and these focus specifically on the impact of an energy deficit. Indeed, an acute, moderate energy deficit (∼80% of estimated energy requirements) that promoted ∼1.0 kg weight loss over 10 days amongst young healthy volunteers resulted in a 16% reduction in MPS at rest despite moderate dietary protein intake (1.5 $g \cdot kg^{-1} \cdot day^{-1}$), with corresponding reductions in signaling pathways involved in the protein translation protein E4-EBP1 (53). Similar findings were observed following 5 days of energy restriction (energy availability of 30 $kcal \cdot kg\ FFM^{-1} \cdot day^{-1}$), resulting in ∼30% reduction in MPS amongst a group of young resistance trained volunteers, with corresponding reductions in activation of mTOR and P70S6K, protein kinases that regulate protein synthesis (54). However, a single resistance training session was able to restore MPS to levels observed in energy balance and this was further enhanced by protein ingestion (15–30 g) post-exercise, resulting in elevation of MPS ∼30% above those observed at rest when in energy balance. Taken together, these acute investigations confirm an energy deficit can impair the molecular machinery involved in protein synthesis, but the overall impact on MPS will depend on other relevant factors such as dietary protein intake and resistance exercise.

The complex interaction between resistance training and diet in an energy deficit has also been explored chronically. In one study, 21 obese women were randomized to either a control arm or a resistance training arm and fed a very low energy liquid formula diet (3,369 $kJ \cdot day^{-1}$ containing 80 g protein, 97 g carbohydrate, 10 g fat) for 90 days. The control group and weight training group lost 16.2 and 16.8% of their body mass, respectively. Changes in body mass, FM, and FFM were similar between groups. However, muscle biopsies revealed an increase in the cross-sectional area of fast twitch muscle fibers (55). In another study on 31 women (69 ± 12 kg, 164 ± 6 cm) who engaged in 24 weeks of combined resistance and endurance training found that the cross-sectional area of thigh muscle, measured by magnetic resonance imaging, increased 7 cm, despite a 2.2% loss in body mass throughout the study (56). Similar gains in lean body mass (LBM) have been observed amongst resistance training naive overweight males in response to regular training (6 days per week, including two resistance training sessions weekly) and a higher protein diet (2.4 $g \cdot kg^{-1} \cdot day^{-1}$), despite a substantial energy deficit (∼60% of estimated energy requirements) (34). Thus, skeletal muscle hypertrophy is possible in an energy deficit, but we propose this response may be more likely among resistance training naive, overweight, or obese individuals. The influence of training status on resistance training response to adjustments in energy balance warrants further investigation.

To our knowledge, there are no rigorously controlled investigations to date that have directly assessed the role of an energy surplus on resistance training outcomes such as skeletal muscle hypertrophy and strength/power traits over an extended period of time. However, there is an array of circumferential evidence to support the idea that an energy surplus does enhance gains in FFM, even independent of the resistance training stimulus. In an early overfeeding study in which 12 pairs of identical male twins were fed a total energy surplus of 353 MJ (with 15% of total daily energy intake from protein) over a span of 100 days (or 4,200 kJ·day^{-1}), the volunteers gained an average of 5.4 kg FM and 2.7 kg FFM (45), despite maintaining a relatively sedentary lifestyle. There was a high level of intra-pair correlation among twins, but significant variance between groups of twins, indicating a significant genetic contribution to the adaptation. Another overfeeding study explored the effect of a similar energy surplus (∼40% above estimated daily needs or ∼4,000 kJ energy surplus daily) but with varying levels of protein intake (5, 15, or 25% of total energy intake) on body composition over an 8-week period. While all groups increased body fat by similar amounts (∼3.5 kg) during this tightly controlled metabolic unit investigation, gains in LBM (∼3 kg) were only evident with the two higher protein intakes, suggesting a minimum amount of dietary protein is necessary to facilitate gains in LBM, even in an energy surplus (23).

In a preliminary exploration of the combined effects of an energy surplus and resistance training, it was found that only those individuals who consumed an energy dense liquid supplement twice daily on training days observed significant gains in body mass and FFM, as inferred via hydrodensitometry, over an 8-week training period (57). Furthermore, there was no difference in response whether the extra energy was consumed as carbohydrate or a combination of carbohydrate and protein, suggesting the energy content of the diet had the biggest impact on body composition changes when dietary protein intake is already adequate. This is supported by earlier pilot work on the influence of an energy surplus on resistance training adaptations (58). Interestingly, while both investigations confirmed a favorable influence of an energy surplus on FFM gains, this was not reflected in strength changes, perhaps because of the brief duration of training or due to nuances in the techniques used to assess strength and body composition. A recently published pilot study on male bodybuilders also supports the concept of greater body mass and muscle mass gains with a more aggressive energy intake (282 kJ·kg^{-1}·day^{-1}), although further inferences from this study are difficult due to methodological concerns (59).

While much still needs to be done to understand the precise role an energy surplus has in facilitating skeletal muscle hypertrophy, the following discussion explores what is known about the magnitude of a surplus, macronutrient composition, and the mechanisms surrounding the role an energy surplus has on skeletal muscle hypertrophy. Given the lack of research within this environment, exploration of overfeeding studies, independent of the resistance training stimulus, are included in the discussion on this topic. This needs to be considered given the influence resistance training has on protein metabolism, highlighting the symbiotic influence of training, and diet on resistance training adaptations.

ENERGY SURPLUS... HOW MUCH

Common text book recommendations for the energy surplus required to gain 1 kg of SMM range from ∼1,500 to 2,000 kJ·day^{-1} in weight stable athletes to an additional 4,000 kJ·day^{-1} in individuals who struggle with lean mass gains or during heavy training loads (31, 32). Guidance on the energy surplus necessary to facilitate skeletal muscle hypertrophy is often based solely on the foundation that if 1 kg of skeletal muscle is 75% water, 20% protein, and 5% fat, glycogen and other minerals and metabolites, then the energy required to accumulate such tissue must at a minimum equal the sum of its parts. Given the assumed composition of skeletal muscle, the energy stored in 1 kg of muscle is ∼5,000–5,200 kJ, with ∼3,400 kJ from protein, ∼1,400–1,500 kJ from fat, and ∼300–450 kJ from muscle glycogen. Furthermore, energy intake should also be sufficient to supply substrate to fuel the protein synthetic machinery stimulated by resistance exercise, a potentially costly process (11, 60). Finally, adequate energy may be needed to account for the increased metabolic cost of accumulated muscle mass and diet induced thermogenesis (DIT), all while minimizing additional energy stored as FM. However, the foundations of these estimates fail to recognize the complicated and energetically expensive process of tissue accretion, an energy value which remains to be systematically quantified. To date, the authors are not aware of any studies that have clearly demonstrated a consistent energy cost of tissue accumulation, specifically that which is associated with skeletal muscle hypertrophy in response to a resistance training stimulus.

Throughout the twentieth century numerous obesity researchers investigated the influence an energy surplus has on body composition. Most studies consistently demonstrate a strong association between body mass gain and the energy surplus (61). However, there is large inter-individual variability in the composition of this mass gain with between 33 and 40% of body mass accretion accounted for by increases in FFM (61). In non-exercising populations some have suggested that the composition of tissue change associated with an energy surplus is a fixed relationship (62), but in athletic populations where exercise and adequate protein intake are the main stimuli for SMM adaptation, this seems unlikely. Of interest from this obesity research is Forbes and colleagues attempt to estimate the energy cost of tissue deposition by using theoretical values of deposition and comparing them to their own findings (22). They reported that by using the values suggested by Spady et al. (63), which were 36.2 kJ·g^{-1} of protein and 50.2 kJ·g^{-1} of fat deposited, in combination with composition ratios of FM:FFM observed in their research, that the energy cost of depositing 1 kg was closely aligned with theoretical values (31,600 and 33,800 kJ·kg^{-1}, respectively). As part of this, Forbes surmised that due to SMM being 20% protein and 75% water, the energy cost of depositing 1 kg of SMM was 7,440 kJ·kg^{-1}. More recently, Joosen and Westerp (61) have suggested a figure of 29.4 kJ·g^{-1}

of protein deposition, potentially reducing the cost of SMM deposition to 6,050 kJ·kg^{-1}. Both estimates suggest an additional energy cost to deposit tissue above the energy density of the substrate (i.e., 16.7 kJ·g^{-1} for protein) of between 12.7 and 19.5 kJ·g^{-1} protein after overfeeding in non-exercising individuals.

As previously highlighted, research suggests considerable inter-individual variability in body mass and composition changes associated with an energy surplus, perhaps as a consequence of genetics (40, 45) or metabolic responses such as adaptation to DIT or non-exercise activity thermogenesis (NEAT) (18, 64). Numerous mathematical models have been published to predict changes in body composition associated with changes in dietary intake and energy expenditure (65, 66). However, these equations often standardize estimates of whole-body metabolic energy flux due to the non-exercising population they are focused on (e.g., no change in glycogen state over time, constant relationships between FM and FFM based on population norms). In athletic populations, the nature of training for body composition alterations significantly influences exercise energy expenditure and confounds the ratios of tissue deposition these models rely on. Therefore, if practitioners are to provide guidelines on the energy surplus necessary to synthesize 1 kg of SMM with minimal FM change, it is necessary that a more expansive model of energy cost be explored.

A recent review of studies investigating the combination of a protein focused energy surplus with resistance training have indicated favorable improvements in LBM accretion (46). However, to date few studies have focused on a titrated energy surplus to ascertain the exact energy and nutrient cost of SMM accretion. It seems to the authors that the energy cost of SMM accretion would be accounted for by consideration of several issues. These include the energy stored within muscle tissue, the energy cost of resistance exercise plus any associated post-exercise elevation in metabolism, the energy cost of any subsequent tissue generation, plus it's subsequent metabolic function. The metabolic adjustments that occur in response to an energy surplus also need to be considered. **Figure 1** provides an overview of factors contributing to the energy cost of skeletal muscle hypertrophy. An appreciation of the magnitude of these factors would provide greater insight into appropriate energy intake prescription to facilitate quality weight gain i.e., weight gain characterized primarily by gains in FFM.

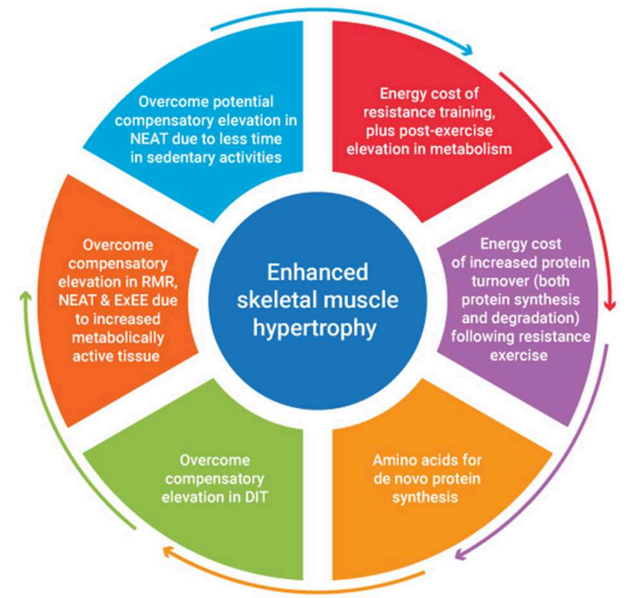

FIGURE 1 | An overview of factors contributing to the energy cost of skeletal muscle hypertrophy.

Numerous studies have attempted to estimate the energy cost of single (67), multiple set (68), and varying speed and intensity (69) resistance exercise sessions, with the net energy cost of an 8 exercise (2 sets of 8–10 repetitions per exercise) hypertrophy program lasting ∼30 min being ∼300 and 600 kJ, for females and males, respectively (70, 71). These sex differences in net energy expenditure are not evident when normalized for lean mass (72). Given the potential importance of quantifying energy expenditure, estimates of net resistance training energy expenditure are available i.e., total energy expenditure (TEE) minus resting energy expenditure or the specific energy cost of the resistance training alone. Mookerjee et al. (68) report the energy cost of undertaking 3 sets of 10 reps at 70% of one repetition maximum across five upper body exercises (369.4 ± 174.1 kJ), equating to an energy expenditure of ∼0.10–0.12 kJ·kg^{-1} LBM·min^{-1}. More recently, a regression equation has been established to estimate resistance training relative energy expenditure based on several variables including stature, age, FM, LBM, and total exercise volume (72), giving practitioners several options to assist with quantifying the energy cost of resistance training. While some of these estimates fail to account for any elevation in energy expenditure post exercise, this effect may only be evident for upwards of 20 min post exercise (72), and thus may be considered negligible, at least following shorter duration resistance training. The metabolic implications of resistance training warrant further exploration.

Given skeletal MPS is elevated for upwards of 24–48 h after resistance exercise, the high metabolic cost of protein synthesis needs to also be accounted for (60, 73, 74). The process of translation elongation is likely to account for a large portion of the synthetic cost with 4 high energy phosphate bonds per peptide bond formed required or 3.6 kJ·g^{-1} of protein synthesized (75). Although significant, translation is one of many energy requiring steps in protein synthesis, with processes such as transcription, folding and movement of proteins within cells all being energy dependent (52). The high energy cost of protein synthesis and the duration over which protein synthetic machinery can be upregulated clearly highlights an underestimated cost of protein synthesis and thus, muscle mass accretion. While any associated increase in protein breakdown has been considered to be negligible, this is unlikely the case (52). Further research is needed to better quantify the energy cost of protein synthesis and degradation, plus the time frame over which this may impact energy needs.

Any increase in LBM will also increase energy expenditure, both at rest and during exercise due to the addition of metabolically active tissue, but the implications of this are likely substantially less than is often presumed. Indeed, estimates of the metabolic activity of individual components of FFM suggest skeletal muscle has an energy cost of just 54 $kJ \cdot kg^{-1} \cdot day^{-1}$ (76, 77). Given this, the elevation in REE in response to a 1–2 kg gain in muscle mass is likely very small (i.e., ∼100 kJ), and within the precision error of indirect calorimetry techniques available to quantify REE (78). Less is known about the impact of both training and an energy surplus on high metabolic activity tissues like internal organs. However, just 3 weeks of energy restriction has been shown to significantly decrease liver and kidney mass, with associated reductions in REE (79), confirming manipulation of energy balance may impact high metabolic activity tissue size and thus presumably energy expenditure.

Any adjustment in energy intake away from energy balance results in an adaptive change in energy expenditure, via adjustments in NEAT, DIT, and/or adaptive thermogenesis (AT). Indeed, energy expenditure has been observed to increase after just 24 h in an energy surplus (40% above estimated needs), at least when protein intake is concomitantly increased (25). It has also been proposed that overfeeding induces an increase in heat production from the food consumed as a protective mechanism against obesity, a process termed luxuskonsumption which is claimed to dissipate upwards of 30% of the excess energy consumed (64). This form of AT has more recently been challenged by Muller et al. (80) with their assessment of overfeeding literature suggesting in most studies 60–70% of excess energy was stored and a further 20–30% accounted for by metabolic lean mass accretion and increased cost of movement leaving only about 10% of energy expenditure not explained and likely accounted for by errors of measurement. One component of TEE that increases based on changes to the baseline food consumption is DIT. The DIT associated with a typical western diet accounts for ∼8–15% of TEE, depending on the macronutrient breakdown of the diet (81). In a review of 26 studies investigating DIT, Quatela et al. (82) used a mixed model meta-regression process to estimate DIT associated with overfeeding. They suggested for every 100 kJ of additional energy from a mixed diet, DIT increased by 1.1 $kJ \cdot h^{-1}$. Energy surpluses associated with higher protein intakes >3.0 $g \cdot kg^{-1}$ BM are likely to increase this figure further and potentially add an additional energy requirement compared to surpluses with energy coming from carbohydrate and fat. This could require an additional 500 kJ a day for athletes with protein intakes in the rage of 3.0 $g \cdot kg^{-1} \cdot day^{-1}$ compared to intakes of 1.0 $g \cdot kg^{-1} \cdot day^{-1}$. Another significant component of TEE that is highly variable in exercising individuals, and may be influenced by training and eating, is NEAT (83). Levine et al. (84) observed a significant increase in NEAT (1,380 $\pm$ 1,080 $kJ \cdot day^{-1}$) among individuals over feed 4,200 $kJ \cdot day^{-1}$ for 56 days. Although there are some arguments against this response (64), it is likely this component of TEE may be highly variable among individuals with different physical activity levels when in an energy surplus.

Finally, the influence dietary energy intake has on the anabolic hormonal environment is becoming better understood. It is now well-established that energy restriction can significantly influence anabolic hormones in exercising individuals, potentially impairing their ability to gain and maintain LBM (85). Although early research by Forbes and colleagues suggested that an energy surplus could improve anabolic hormone levels in women (86), few other studies have demonstrated significant increases in the hormonal environment in response to an energy surplus (87, 88). Irrespective, such acute elevations in circulating anabolic hormones may have little, if any, impact on resistance training adaptations (89, 90). Thus, any benefit of an energy surplus is likely mediated via mechanisms other than acutely influencing the anabolic hormonal environment.

What is clear from the existing literature is that there is yet to be defined a single evidence-based energy estimate for accretion of 1 kg of SMM. This is most likely because of the impact of individual presenting nuances (age, genetics, prior training experience, sex, body composition) as well as adaptation to the energy surplus. **Figure 2** provides a theoretical overview of the energy cost of generating SMM typically reported amongst resistance training individuals (91), the results of which are similar to that estimated previously (22). A better understanding of these variables and their impact on resistance training induced skeletal muscle hypertrophy may afford better individual prescription of the energy surplus. Until then, practitioners are advised to take a conservative approach to creating an energy surplus, within the range of ∼1,500–2,000 $kJ \cdot day^{-1}$, to minimize FM gains, with regular review of body composition and functional capacities like strength to further personalize dietary intake.

ENERGY SURPLUS… MACRONUTRIENT CONSIDERATIONS

Within the constraints of an athlete's total daily energy intake, considering appropriate allocation of protein, carbohydrate, and fat may also have a measurable impact on skeletal muscle hypertrophy. Dietary protein has long been identified as a critical macronutrient to consider in skeletal muscle repair and synthesis. Indeed, resistance trained athletes have advocated high protein diets for many years (10). While debate continues on the need for additional protein amongst athletes, general guidelines now recommend that athletes undertaking resistance training ingest approximately twice the current recommendations for protein of their sedentary counterparts or as much as 1.6–2.2 $g \cdot kg^{-1} \cdot day^{-1}$ (92). In a recent meta-regression of 49 studies including 1,863 male and female participants, the protein intake associated with the greatest gains in muscle mass was 1.6 $g \cdot kg^{-1} \cdot day^{-1}$ (18). Exceeding this upper range of protein intake guidelines likely offers no further benefit and simply promotes increased amino acid catabolism and protein oxidation (14). Even extremely high protein intakes, up to double that advocated (18), does not further facilitate skeletal muscle hypertrophy or strength gains (93–95).

Despite a lack of apparent benefits from a high protein diet, athletes who are particularly sensitive to gains in FM may be tempted to source additional energy to facilitate an energy surplus from protein, given it is suggested to be less lipogenic, presumably because of increased DIT (96). However,

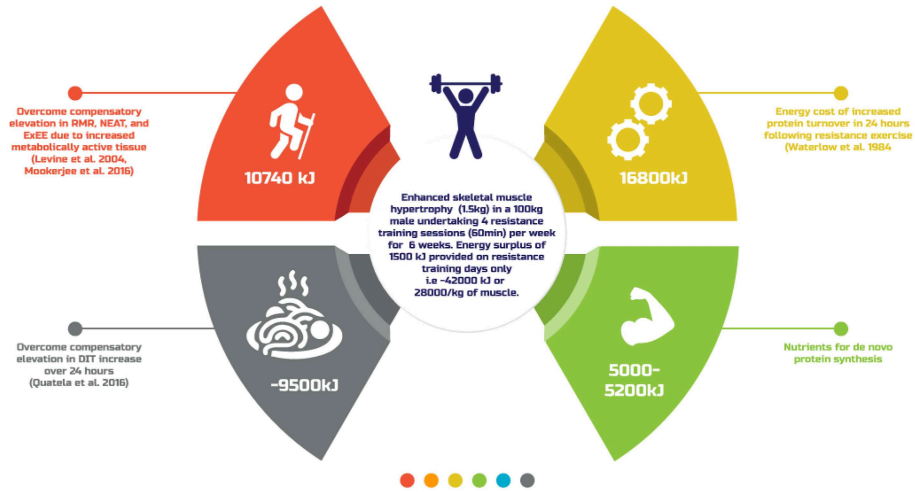

FIGURE 2 | A theoretical overview of the energy cost of generating skeletal muscle mass typically reported amongst resistance training individuals.

the impact on DIT is small in absolute terms and thus unlikely to significantly influence the response to an energy surplus (97). While it has been claimed protein, and thus energy intake, can be increased substantially without promoting gains in FM (93–95, 98), it is difficult to understand how this is possible, even after considering the impact on DIT. Indeed, tightly controlled research exploring the impact of variable protein intakes while overfeeding in a metabolic hospital ward confirms protein intake impacts lean mass while the energy surplus alone contributes to increases in FM, at least amongst sedentary individuals (23).

Despite previous concerns that high protein diets may be harmful, healthy adults with protein intakes of 1.8 $g \cdot kg^{-1} \cdot day^{-1}$ show no adverse effect on renal function (99). Furthermore, very high protein diets (2.5–3.3 $g \cdot kg^{-1} \cdot day^{-1}$) consumed over a year had no deleterious effects on blood lipids, liver, or renal function (100). However, the health implications of very high protein diets over longer periods is yet to be elucidated. Taken collectively, it is hard to justify the very high protein intakes consumed by some resistance training athletes, given the current lack of supporting research in enhancing resistance training adaptations, nor research confirming such high intakes are without health implications.

In addition to protein requirements, consideration must also be given to appropriate allocation of carbohydrate and fat in a meal plan attempting to facilitate muscle hypertrophy. Short term overfeeding studies in sedentary populations confirm there is no significant difference in body composition changes whether the energy surplus comes predominantly from carbohydrate or fat (101, 102). However, the metabolic implications of exercise must be considered amongst resistance trained individuals. Given the primary substrate used during resistance training is carbohydrate (103), it is logical to explore the provision of additional carbohydrate to help support training demands. This may be especially so for athletes other than weightlifters, powerlifters, and bodybuilders, where resistance training is typically undertaken as an ancillary form of training to complement sport specific training. Resistance training can reduce muscle glycogen stores by 30–40% (104). Therefore, larger volume, hypertrophy focused resistance training may necessitate additional carbohydrate to facilitate resistance training work capacity (105, 106) and restore muscle glycogen (107). While it is difficult to confirm further enhancement in acute training capacity (108) or chronic body composition adaptations (58), when contrasting a moderate vs. high carbohydrate intake, a chronic restrictive carbohydrate intake may impair resistance training adaptations. Indeed, SMM gains have consistently been impaired in studies of resistance trained individuals following high fat, "ketogenic" diets when compared to moderate intakes (109–111). Given this, it seems reasonable to continue to support carbohydrate intakes within the range of 4–7 $g \cdot kg^{-1} \cdot day^{-1}$ for strength trained athletes (112), with upper ranges advocated for those undertaking resistance exercise as an ancillary form of training to complement sport specific training.

The American College of Sports Medicine advises athletes to keep fat intakes in line with general health guidelines (113), which constitutes 20–35% of energy intake. Athletes should be discouraged from fat intakes below 15–20% of energy intake since such restrictions likely moderate the energy density of a meal plan, making it challenging to facilitate an energy surplus while also reducing intake and absorption of fat-soluble vitamins (114, 115). Furthermore, reducing dietary fat from 33.3 to 13.9% of total energy intake resulted in modest but significant reductions in resting testosterone concentrations (116), a result which has been replicated elsewhere (117, 118). However, the relevance of these small changes in circulating androgens is unknown in the context of chronic resistance training adaptation.

Given the energy density of fat is effectively double that of carbohydrate and protein, it is logical to consider increasing fat intake when attempting to increase the energy density of a meal plan. Indeed, within hypermetabolic clinical conditions such as cystic fibrosis requiring a high energy intake, increasing fat intake is advocated (119). Fat source may also determine the fate of excess energy, with polyunsaturated fat more likely to promote gains in lean mass compared to saturated fat, which is more likely to result in ectopic and general fat accumulation in normal weight volunteers (120). Evolving evidence suggests omega-3 polyunsaturated fatty acid ingestion enhances the anabolic response to nutritional stimuli and increases muscle mass and function in young and middle-aged males (121), plus older adults (122), respectively, independent of the resistance training stimuli. There are also health benefits to consider in the type of fat consumed. Postprandial fat oxidation is higher after monounsaturated (olive oil) compared to saturated (cream) fat meals (123). Simply substituting saturated fat for unsaturated fat, predominantly as monounsaturated fat, was enough to induce favorable improvements in lipid profile and reductions in fat mass in a small sample of overweight and obese males (124). Whilst interesting, further research is required to determine whether the potential benefits in the type of fat ingested are maintained in an athletic population undergoing resistance training in an energy surplus and whether this influences the quality of weight gain. Until then, international recommendations indicate that active individuals may consume up to 35% of their daily energy intake from dietary fat, with saturated fatty acids not exceeding 10% of total energy intake (114).

The type of foods from which macronutrients are sourced may also have implications on lean mass gains. Protein type is important as high biological value protein sources rich in leucine are recommended to maximize protein synthetic rates (125). Consumption of protein in its natural whole-food matrix may also differentially stimulate muscle anabolic properties compared to isolated proteins particularly post resistance training (126). This has been observed with whole milk compared to skim milk (127), and whole eggs compared to egg whites (126). Thus, additional nutrients found in whole foods may offer advantages beyond their amino acid profile to maximize protein synthesis (128), although more research is required to ascertain how this occurs and if benefits remain when total dietary protein and energy is matched.

In conclusion, insufficient data exists to promote an energy surplus that comes primarily from any specific macronutrient. Thus, without further research we can only emphasize that the minimum intakes of macronutrients advised in this section be achieved while ensuring an appropriate energy surplus. Preliminary evidence suggests extra protein may be less lipogenic, perhaps because of an increase in energy expenditure associated with DIT, although this needs to be confirmed with better controlled studies on resistance training populations and may need to merely be corrected by further increasing energy intake if the same energy surplus is desired. Furthermore, the health implications of sustained protein intakes above $\sim$2.5 $g{\cdot}kg^{-1}{\cdot}day^{-1}$ remain to be validated. As such, other factors such as individual preference, allocation of extra energy over the day relative to resistance training, existing energy density of the meal plan and potential for increasing the volume of existing food/ fluid intake may be a higher priority when considering the source of any prescribed energy surplus.

ENERGY SURPLUS… NUTRIENT TIMING

Nutrient timing has received significant attention in recent years (129), with interventions aiming to optimize work capacity during exercise and/or facilitate training adaptations. Specifically, primary attention has been given to the timing of protein and carbohydrate intake to support acute fuelling and recovery goals (130), plus facilitate chronic skeletal muscle hypertrophy adaptations (18). However, whenever daily macronutrient distribution is adjusted, so too potentially is energy intake. Thus, the influence of daily energy distribution, including the number of eating occasions, also warrants consideration.

Athletes are encouraged to pay attention to dietary intake pre, during and post exercise, under the assumption that nutritional strategies can influence both acute resistance exercise capacity and/ or training induced adaptations. Indeed, evidence is present for a beneficial role of acute carbohydrate ingestion before and/ or during strength training (105, 131). However, not all investigations show a benefit of acute carbohydrate ingestion (132–134), suggesting the ergogenic potential for carbohydrate ingestion is most likely to be observed when athletes are undertaking longer-duration, high-volume resistance training in isolation, or when resistance training is incorporated into a higher volume total training load that also includes sports specific training. Currently, specific recommendations for an optimum rate or timing of carbohydrate ingestion for resistance trained athletes before and during a resistance training session cannot be made within broader guidance of 4–7 $g{\cdot}kg^{-1}$ body mass daily (112). However, this warrants investigation given the potential for enhanced substrate availability, plus better alignment of energy intake to expenditure.

The consumption of high biological value protein containing meals/snacks in close proximity to training is widely applied as a strategy to augment the skeletal muscle adaptive response to resistance exercise (135). Less is known about the impact of protein distribution in the meal plan outside of the acute period before and/or after exercise (<3 h). There is some evidence to suggest that skeletal MPS may be enhanced with a wider distribution of daily protein intake compared with an acute bolus of protein (17). Indeed, spacing protein-containing meals ($\sim$0.3 $g{\cdot}kg^{-1}$ of high biological value protein) every 3–5 h throughout the waking period of the day has been advocated when attempting to maximizes MPS (92), although this remains to be validated amongst resistance trained individuals when ingesting protein as part of mixed macronutrient meals while in energy balance or surplus. Indeed, increasing daily distribution of high biological value protein from four to six meals per day had no influence of pre-season gains in lean body mass amongst a group of rugby athletes (91), suggesting a threshold of daily protein containing meals, above which there is likely no further enhancement in skeletal muscle hypertrophy when in energy balance/surplus, perhaps due to the hypothesized refractory period that follows acute protein ingestion (136).

While skeletal MPS is unlikely to be further enhanced by more frequent eating occasions, smaller more frequent eating occasions (5–6+) are advocated when attempting to increase muscle mass, presumably because gastrointestinal tract tolerance is higher with more frequent eating occasions compared to merely increasing the size of existing eating occasions (31). Indeed, smaller, more frequent meals are advocated clinically in the management of early satiety, anorexia and gastrointestinal symptoms (137). Emerging evidence supports this notion, with significantly stronger hunger and desire to eat when following a smaller, more frequent eating pattern (138). This is corroborated by preliminary data in elite athletes, with a moderate association between meal frequency and total energy intake (139). Given that snacks accounted for approximately one-quarter of total energy intake in this athletic population, it seems pertinent to advocate the inclusion of snacks in the meal pattern of athletes attempting to increase overall energy intake. Current evidence suggests athletes ingest food daily typically over ∼5 eating occasions, including the three main meals, plus snacks (139, 140). The impact of eating occasion frequency on overall nutrient intake and subsequent resistance training outcomes warrants investigation in athletic populations. Until then, athletes are encouraged to consume a minimum of 3 main meals, with the use of strategic snacks to support fuelling and recovery goals, plus facilitate skeletal MPS.

Similar to the general population (141), athletes allocate more of their daily energy intake to the later part of the day (140, 142). The impact of better alignment of daily energy intake to expenditure, or within day energy balance, is an emerging area of research interest focused on the physiological implications of real-time changes in energy intake and expenditure. Preliminary research suggests unfavorable metabolic and endocrine perturbations with large acute or extended energy deficits amongst athletes focused on leanness (143–145). The implications of manipulating within day energy balance amongst resistance training athletes attempting to promote quality weight gain has not been investigated but warrants consideration.

There is some preliminary evidence to suggest better alignment of energy intake to expenditure may have application in facilitating resistance training outcomes. Ingestion of a creatine monohydrate containing carbohydrate-protein supplement immediately before and after resistance training results in more favorable resistance training adaptations than when the same supplement is ingested away from training (146), although this is not always evident, at least when a lower energy, protein only supplement is ingested according to a similar time frame (147). While it is impossible to ascribe this effect to the timing of macronutrient or energy intake, this approach toward optimizing nutrition support before and after a resistance training session also supports general fuelling and recovery goals. It also better aligns acute energy intake to expenditure, given daily energy expenditure is likely highest during exercise.

For athletes focused on facilitating quality weight gain, consideration of temporal energy patterns may also be warranted given preliminary research suggesting an association between eating more of the day's total energy intake at night and obesity (148, 149). This may be due to the metabolic dysfunction induced by delayed eating, even amongst normal weight individuals (150), or it may merely reflect behavioral mechanisms that influence appetite control (151). Indeed, intake in the late night also appears to lack satiating value, resulting in greater overall daily intake (152). While tempting to advocate athletes to "front end" more of the daily energy intake, especially amongst individuals aiming to minimize fat mass gains, moderating energy intake as the day progresses may be inappropriate for those with high energy needs and/ or those with significant training commitments in the evening. Indeed, there is evidence of enhanced strength and muscle mass gains from resistance training undertaken in the evening when two protein containing meals are ingested prior to bed compared to one (153). As such, manipulation of daily energy distribution should merely be a variable practitioners consider when providing advice to athletes, adjusting according to the individual athlete and their unique circumstances, including specific energy needs, timing of training, and nutrition goals. The influence of daily energy distribution warrants investigation amongst resistance trained athletes attempting to facilitate quality weight gain.

While it is logical to encourage energy intake to vary over a training week to reflect exercise energy expenditure, athletes do not always adjust intake to reflect expenditure (154), perhaps in part because of the variable impact exercise has on appetite (155). If the creation of a positive energy balance is desired to facilitate resistance training adaptations, one variable to consider is whether that energy surplus should be applied throughout the week or just on resistance training days. Supplemental energy has typically only been provided on resistance training days in the limited research in which a positive energy balance has been achieved in conjunction with resistance training (57). While this better mirrors energy intake to expenditure, it could be argued given that skeletal MPS is elevated for upwards of 48 h following a single resistance training session (43), that a positive energy balance is also warranted for upwards of 24–48 h post training. Presumably the creation of a positive energy balance on both resistance training and non-training days may help to optimize the potential for enhanced skeletal muscle hypertrophy. This issue warrants further investigation in resistance trained populations, especially amongst those individuals aiming to facilitate quality weight gain. The concept of intermittent energy restriction shows preliminary potential for facilitating more effective quality weight loss by moderating any associated metabolic adjustments (156). It would be interesting to explore if the reverse was also true with the intermittent application of a positive energy balance for facilitating quality weight gain. Indeed, there is preliminary evidence to suggest an acute energy surplus (facilitated via an increase in all macronutrients) results in preferential gains in fat free mass (157).

MANAGING SATIETY

Attempts to increase total energy intake by merely increasing the total volume of food ingested may result in early satiety, limiting the potential for creation of an energy surplus. Thus, consideration may need to be given to increasing the energy density of the meal plan. While increasing dietary fat intake is a logical option, other novel strategies to better manage early satiety include changing the food form. For example, regardless of the predominant energy source, drinks have lower satiety than solid foods and thus, provide greater potential for facilitating a positive energy balance (158, 159). Furthermore, nutritious drinks can be particularly practical following exercise when the appetite may be suppressed, while also supporting nutritional recovery goals. A high intake of low energy density vegetables may also moderate total energy intake at a meal (160). However, given the health benefits of individuals achieving public health guidance on vegetable intake (161), practitioners are advised to balance the pursuit of enhancing energy density with overall health benefits of the meal plan. Advocating the ingestion of only moderate servings of protein rich foods at meals may also be appropriate, given the satiating effect of protein (162), although the implications of higher protein meals on satiety when in a positive energy balance remain to be confirmed. However, given moderate protein servings will also help optimize the skeletal muscle protein synthetic response (92), guidance on moderated protein servings appears logical.

FUTURE DIRECTIONS

Further research into this area is clearly warranted, but challenged by individual responsiveness, including the potential for rapid metabolic adjustment to the energy surplus and the need to consider not only the energy surplus, but potentially where that energy comes from and how it is allocated in the meal plan over the day relative to the resistance training stimulus. Methodological issues associated with the quantification of key outcome measures such as energy intake, energy expenditure and body composition are also very relevant when attempting to interpret the literature. For example, an increase in dietary carbohydrate intake to facilitate a positive energy balance will acutely increase muscle metabolites and associated water content, significantly influencing estimates of body composition via dual energy x-ray absorptiometry (163), and other commonly used techniques, including air displacement plethysmography and bioimpedance analysis (164), while acute resistance exercise induced water retention can influence magnetic resonance imaging estimates of muscle cross-sectional area for at least 52 h (165). Given such physique assessment nuances, concurrent review of associated functional capacity adaptations would appear pertinent for future investigations.

Several gaps in the literature have been identified in this review, which warrant further exploration. Some of these are expanded upon here in the hope of facilitating research interest in this area. A broader understanding of these issues has the potential to not only impact on dietary guidance for athletic populations, but also clinical populations where retention or promotion of SMM is advocated.

Should the Prescribed Energy Surplus Be Adjusted Based on the Anticipated Muscle Hypertrophy Potential of the Athlete?

Younger, less experienced athletes have a greater potential for skeletal muscle hypertrophy in response to resistance training than their more experienced counterparts (38). It could be argued that if the energy surplus is merely required to contribute the building blocks of newly generated tissue, then the prescribed energy surplus should be adjusted based on muscle hypertrophy potential. Preliminary research in a small group of elite Norwegian athletes supports this hypothesis (166). However, if the energy surplus facilitates a physiological response that amplifies the anabolic signal created by resistance training, then perhaps the energy surplus should be maintained in experienced athletes, at least in these where muscle hypertrophy and strength gains are prioritized over short term FM increments.

What Factors Influence Whether Endogenous and/or Exogenous Energy Sources Can Support the Energy Cost of Muscle Hypertrophy?

The presence of muscle hypertrophy in response to resistance training while in an energy deficit clearly confirms the energy cost of hypertrophy can be obtained endogenously (34, 55, 56), but is more likely evident amongst resistance training naïve, overweight individuals. Thus, individual nuances such as presenting energy status and training history may need to be considered when prescribing energy intake.

Does Better Temporal Alignment of Daily Energy Intake to Expenditure (Within Day and Between Day) Result in More Favorable Gains in FFM Relative to FM When in an Energy Surplus?

While preliminary research suggests unfavorable metabolic and endocrine perturbations with large acute, within day energy deficits amongst athletes (144, 145), less is known about the potential benefit of better aligning daily energy intake to expenditure when in an energy surplus. Encouraging preliminary research indicates a more favorable response to resistance training when more of the daily energy intake is allocated immediately before and after exercise (146). The influence of better aligning daily energy intake to expenditure across a training week also warrants investigation, the results of which would help to identify if any energy surplus should be applied on raining days only or throughout the training week.

CONCLUSIONS

The creation of an energy surplus is commonly advocated by sports nutrition practitioners when attempting to optimize resistance training induced skeletal muscle hypertrophy. Such guidance is often based solely on the assumed energy stored within the tissue being assimilated. Unfortunately, this fails to account for other energetically expensive processes, including the energy cost of tissue generation, plus the metabolic adjustments that occur in response to an energy surplus. An appreciation of the magnitude of these factors would provide greater insight into appropriate energy prescription to facilitate optimal rates of muscle hypertrophy while minimizing fat mass gain. Until that time, practitioners are advised to start conservatively with an energy surplus within the range of ∼1,500–2,000 kJ·day^{-1} and closely monitor response to the intervention, using changes in body composition and functional capacity to further personalize dietary interventions. So long as minimum guidelines for macronutrients advocated for resistance training individuals are achieved, there does not appear to be any metabolic or functional benefit to the source of the energy surplus, affording the practitioner an opportunity to adjust intake based on other variables such as existing energy density of the meal plan, eating occasions and distribution of energy, and macronutrient intake relative to training, plus potential for further increasing food intake.

AUTHOR CONTRIBUTIONS

BD, DM, EH, GS, GJS, and JI drafted, critically reviewed, and revised the manuscript for important intellectual content, contributed to manuscript revision, read, and approved the submitted version.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.